


Silicon

Silicon ( */ˈsɪlɪkən/ SIL-ə-kən or /ˈsɪlɪkɒn/ SIL-ə-kon*; Latin: *silicium*) is the most common metalloid. It is a chemical element, which has the symbol **Si** and atomic number 14. A tetravalent metalloid, it is less reactive than its chemical analog carbon.




Silicon has many industrial uses. It is the principal component of most semiconductor devices, most importantly integrated circuits or *microchips*. Silicon is widely used in semiconductors because it remains a semiconductor at higher temperatures than the semiconductor germanium and because its native oxide is easily grown in a furnace and forms a better semiconductor/dielectric interface than any other material.

In the form of silica and silicates, silicon forms useful glasses, cements, and ceramics. It is also a constituent of silicones, a class-name for various synthetic plastic substances made of silicon, oxygen, carbon and hydrogen, often confused with silicon itself.

Silicon is an essential element in biology, although only tiny traces of it appear to be required by animals.^[6] It is much more important to the metabolism of plants, particularly many grasses, and silicic acid (a type of silica) forms the basis of the striking array of protective shells of the microscopic diatoms.

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aluminium ← silicon → phosphorus <div> <div> C ↑ Si ↓ Ge </div> <div>  ^{14}Si <div>□</div> </div> </div> <div>Periodic table</div>	
Appearance crystalline, reflective with bluish-tinged faces  Silicon is the main component in computer chips.  Spectral lines of Silicon	
General properties	
Name, symbol, number	silicon, Si, 14
Pronunciation	<i>/ˈsɪlɪkən/ SIL-ə-kən</i> or <i>/ˈsɪlɪkən/ SIL-ə-kon</i>
Element category	metalloid
Group, period, block	14, 3, p
Standard atomic weight	$28.0855\text{g}\cdot\text{mol}^{-1}$
Electron configuration	$[\text{Ne}] 3s^2 3p^2$
Electrons per shell	2, 8, 4 (Image)
Physical properties	
Phase	solid
Density (near r.t.)	$2.3290\text{g}\cdot\text{cm}^{-3}$
Liquid density at m.p.	$2.57\text{g}\cdot\text{cm}^{-3}$
Melting point	1687 K, 1414 °C, 2577 °F

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Notable characteristics

The outer electron orbitals (half filled subshell holding up to eight electrons) have the same structure as in carbon and the two elements are sometimes similar chemically. Even though it is a relatively inert element, silicon still reacts with halogens and dilute alkalis, but most acids (except for some hyper-reactive combinations of nitric acid and hydrofluoric acid) do not affect it. Having four bonding electrons however gives it, like carbon, many opportunities to combine with other elements or compounds under the right circumstances.

Both silicon and (in certain aspects) carbon are semiconductors, readily either donating or sharing their four outer electrons allowing many different forms of chemical bonding. Pure silicon has a negative temperature coefficient of resistance, since the number of free charge carriers increases with temperature. The electrical resistance of single crystal silicon significantly changes under the application of mechanical stress due to the piezoresistive effect.

In its crystalline form, pure silicon has a gray color and a metallic luster. It is similar to glass in that it is rather strong, very brittle, and prone to chipping.

Boiling point	2628 K, 2355 ^[1] °C, 4271 °F					
Heat of fusion	50.21 kJ·mol ^{−1}					
Heat of vaporization	359 kJ·mol ^{−1}					
Specific heat capacity	(25 °C) 19.789 J·mol ^{−1} ·K ^{−1}					
Vapor pressure						
P (Pa)	1	10	100	1 k	10 k	100 k
at T (K)	1908	2102	2339	2636	3021	3537
Atomic properties						
Oxidation states	4, 3 , 2 , 1 ^[2] -1, -2, -3, -4 (amphoteric oxide)					
Electronegativity	1.90 (Pauling scale)					
Ionization energies (more)	1st: 786.5 kJ·mol ^{−1}					
	2nd: 1577.1 kJ·mol ^{−1}					
	3rd: 3231.6 kJ·mol ^{−1}					
Atomic radius	111 pm					
Covalent radius	111 pm					
Van der Waals radius	210 pm					
Miscellanea						
Crystal structure	diamond cubic					
Magnetic ordering	diamagnetic ^[3]					
Electrical resistivity	(20 °C) 10 ³ ^[4] Ω·m					
Thermal conductivity	(300 K) 149 W·m ^{−1} ·K ^{−1}					
Thermal expansion	(25 °C) 2.6 μm·m ^{−1} ·K ^{−1}					
Speed of sound (thin rod)	(20 °C) 8433 m/s					
Young's modulus	185 ^[4] GPa					
Shear modulus	52 ^[4] GPa					
Bulk modulus	100 GPa					
Poisson ratio	0.28 ^[4]					
Mohs hardness	7					
CAS registry number	7440-21-3					

Silicon is one of the few substances, like water, bismuth, and gallium; whose density is higher in liquid than in solid state, so it expands when it freezes.

History

Silicon was first identified by Antoine Lavoisier in 1787 (as a component of the Latin *silex*, *silicis* for flint, flints), and was later mistaken by Humphry Davy in 1800 for a compound. In 1811 Gay-Lussac and Thénard probably prepared impure amorphous silicon through the heating of potassium with silicon tetrafluoride. In 1824, Berzelius, generally given credit for discovering the element silicon, prepared amorphous silicon using approximately the same method as Lussac. Berzelius also purified the product by repeatedly washing it.^{[7][8]}

Occurrence

See also: Silicate minerals

Measured by mass, silicon makes up 27.7% of the Earth's crust and is the second most abundant element in the crust, after oxygen. Pure silicon crystals are very rarely found in nature; they can be found as inclusions with gold and in volcanic exhalations. Silicon is usually found in the form of silicon dioxide (also known as quartz), and other more complex silicate minerals.

Silica occurs in minerals consisting of (practically) pure silicon dioxide in different crystalline forms. Amethyst, agate, quartz, rock crystal, chalcedony, flint, jasper, and opal are some of the forms in which silicon dioxide appears. Biogenic silica occurs in the form of diatoms, radiolaria and siliceous sponges.

Silicon also occurs as silicate minerals (various minerals containing silicon, oxygen and one or another metal), for example the feldspar group. These minerals occur in clay, sand and various types of rock such as granite and sandstone. Feldspar, pyroxene, amphibole, and mica are a few of the many common silicate mineral groups.

Silicon is a principal component of many meteorites, and also is a component of obsidian and tektites, which are natural forms of glass.

Isotopes

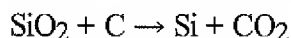
Main article: isotopes of silicon

Silicon has numerous known isotopes, with mass numbers ranging from 22 to 44. ²⁸Si (the most abundant isotope, at 92.23%), ²⁹Si (4.67%), and ³⁰Si (3.1%) are stable; ³²Si is a radioactive isotope produced by cosmic ray spallation of argon. Its half-life has been determined to be approximately 170 years (0.21 MeV), and it decays by beta - emission to ³²P (which has a 14.28 day half-life)^[9] and then to ³²S.

Band gap energy at 300 K	1.12 eV				
Most stable isotopes					
Main article: Isotopes of silicon					
iso	NA	half-life	DM	DE (MeV)	DP
²⁸ Si	92.23%	²⁸ Si is stable with 14 neutrons			
²⁹ Si	4.67%	²⁹ Si is stable with 15 neutrons			
³⁰ Si	3.1%	³⁰ Si is stable with 16 neutrons			
³² Si	trace	170 y	β [−]	13.020	³² P

Production

Silicon is commercially prepared by the reaction of high-purity silica with wood, charcoal, and coal, in an electric arc furnace using carbon electrodes. At temperatures over 1,900 °C (3,450 °F), the carbon reduces the silica to silicon according to the chemical equations:



Liquid silicon collects in the bottom of the furnace, and is then drained and cooled. The silicon produced via this process is called *metallurgical grade silicon* and is at least 98% pure. Using this method, silicon carbide (SiC) may form. However, provided the concentration of SiO₂ is kept high, the silicon carbide can be eliminated:



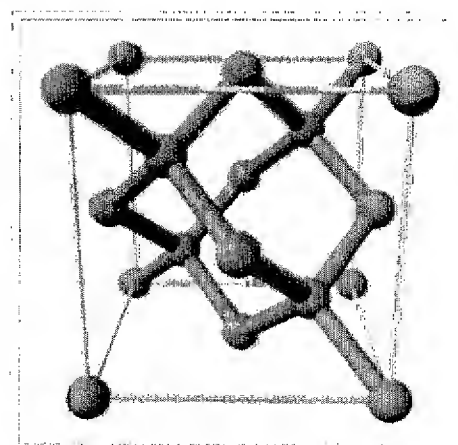
In September 2008, metallurgical grade silicon cost about USD 1.45 per pound (\$3.20/kg),^[10] up from \$0.77 per pound (\$1.70/kg) in 2005.^[11]

Pure silicon (>99.9%) can be extracted directly from solid silica or other silicon compounds by molten salt electrolysis.^{[12][13][14][15]} This method, known from 1854^[16] (see also FFC Cambridge Process) has the potential to directly produce solar grade silicon without any CO₂ emission and at much lower energy consumption.

Crystallization

Further information: Monocrystalline silicon

Silicon, like carbon and germanium, crystallizes in a diamond cubic crystal structure. The lattice spacing for silicon is 0.357 nm (3.57 Å).^[17] The majority of silicon crystals grown for device production are produced by the Czochralski process, (CZ-Si) since it is the cheapest method available and it is capable of producing large size crystals. However, silicon single-crystals grown by the Czochralski method contain impurities since the crucible which contains the melt dissolves. For certain electronic devices, particularly those required for high power applications, silicon grown by the Czochralski method is not pure enough. For these applications, float-zone silicon (FZ-Si) can be used instead. With the CZ-Si method the seed is dipped into the silicon melt, and the growing crystal is pulled upward, whereas with the FZ-Si method the thin seed crystal sustains the growing crystal as well as the polysilicon rod from the bottom. As a result, it is difficult to grow large size crystals using the float-zone method. Today, all the dislocation-free silicon crystals used in semiconductor industry with diameter 300 mm or larger are grown by the Czochralski method with purity level significantly improved.



Silicon crystallizes in the diamond cubic crystal structure

Purification

The use of silicon in semiconductor devices demands a much greater purity than afforded by metallurgical grade silicon. Historically, a number of methods have been used to produce high-purity silicon.

Physical methods

Early silicon purification techniques were based on the fact that if silicon is melted and re-solidified, the last parts of the mass to solidify contain most of the impurities. The earliest method of silicon purification, first described in 1919 and used on a limited basis to make radar components during World War II, involved crushing metallurgical grade silicon and then partially dissolving the silicon powder in an acid. When crushed, the silicon cracked so that the weaker impurity-rich regions were on the outside of the resulting grains of silicon. As a result, the impurity-rich silicon was the first to be dissolved when treated with acid, leaving behind a more pure product.

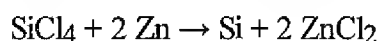
In zone melting, also called zone refining, the first silicon purification method to be widely used industrially, rods of metallurgical grade silicon are heated to melt at one end. Then, the heater is slowly moved down the length of the rod, keeping a small length of the rod molten as the silicon cools and re-solidifies behind it. Since most impurities tend to remain in the molten region rather than re-solidify, when the process is complete, most of the impurities in the rod will have been moved into the end that was the last to be melted. This end is then cut off and discarded, and the process repeated if a still higher purity is desired.

Chemical methods

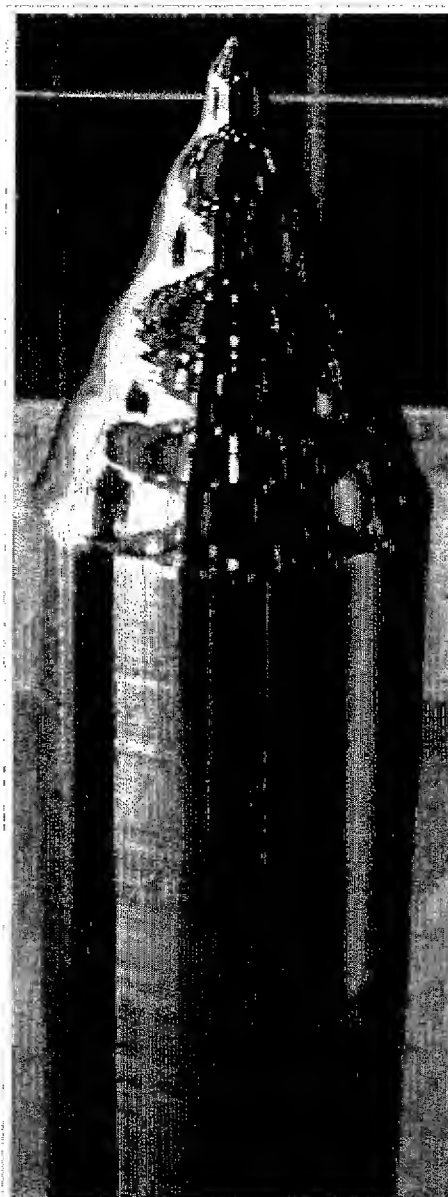
Today, silicon is purified by converting it to a silicon compound that can be more easily purified by distillation than in its original state, and then converting that silicon compound back into pure silicon.

Trichlorosilane is the silicon compound most commonly used as the intermediate, although silicon tetrachloride and silane are also used. When these gases are blown over silicon at high temperature, they decompose to high-purity silicon.

At one time, DuPont produced ultra-pure silicon by reacting silicon tetrachloride with high-purity zinc vapors at 950 °C, producing silicon:

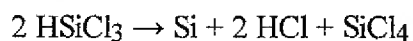


However, this technique was plagued with practical problems (such as the zinc chloride byproduct solidifying and clogging lines) and was eventually abandoned in favor of the Siemens process.



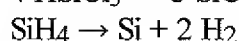
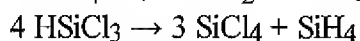
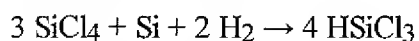
Monocrystalline silicon ingot grown by the Czochralski process

In the **Siemens process**, high-purity silicon rods are exposed to trichlorosilane at 1150 °C. The trichlorosilane gas decomposes and deposits additional silicon onto the rods, enlarging them:



Silicon produced from this and similar processes is called *polycrystalline silicon*. Polycrystalline silicon typically has impurity levels of less than 10^{-9} .

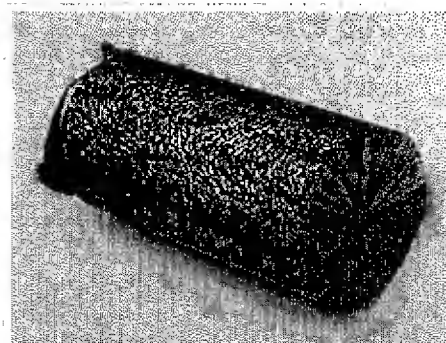
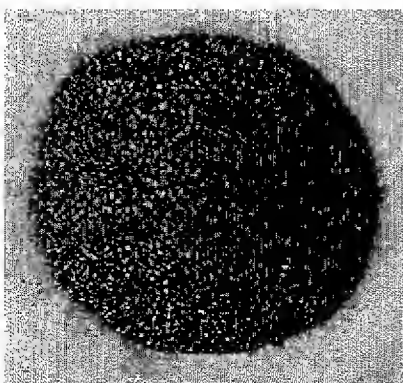
In 2006 REC announced construction of a plant based on fluidized bed technology using silane:^[18]



Different forms of silicon

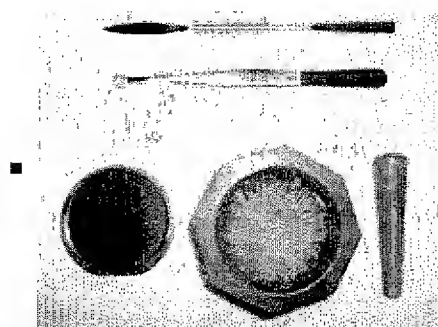


Silicon wafer with mirror finish



A polycrystalline silicon rod made by the Siemens process

Silicon powder



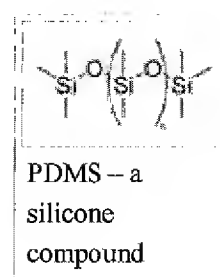
Nanocrystalline silicon powder

One can notice the color change in silicon nanopowder. This is caused by the quantum effects which occur in particles of nanometric dimensions. See also Potential well, Quantum dot, and Nanoparticle.

Compounds

Silicon forms binary compounds called silicides with many metallic elements whose properties range from reactive compounds, e.g. magnesium silicide, Mg_2Si through high melting refractory compounds such as molybdenum disilicide, MoSi_2 .^[19] Silicon carbide, SiC (carborundum) is a hard, high melting solid and a well known abrasive. Silane, SiH_4 , is a pyrophoric gas with a similar tetrahedral structure to methane, CH_4 . Additionally there is a range of catenated silicon hydrides that form a homologous series of compounds, $\text{Si}_n\text{H}_{2n+2}$ where $n = 2\text{--}8$ (analogous to the alkanes).^[20] These are all readily hydrolyzed and are thermally unstable, particularly the heavier

members.^[20] Disilenes contain a silicon-silicon double bond (analogous to the alkenes) and are generally highly reactive requiring large substituent groups to stabilize them.^[21] A disilyne with a silicon-silicon triple bond was first isolated in 2004; although as the compound is non-linear, the bonding is dissimilar to that in alkynes.^[22] Tetrahalides, SiX_4 , are formed with all of the halogens.^[19] Silicon tetrachloride, for example, readily reacts with water; unlike its carbon analogue, carbon tetrachloride.^[20] Silicon dihalides are formed by the high temperature reaction of tetrahalides and silicon; with a structure analogous to a carbene they are reactive compounds.^[20] Silicon difluoride condenses to form a polymeric compound, $(\text{SiF}_2)_n$.^[20] Silicon dioxide is a high melting solid with a number of different crystal forms; the most familiar of which is the mineral quartz.^[19] In quartz each silicon atom is surrounded by four oxygen atoms that bridge to other silicon atoms to form a three dimensional lattice.^[19] Silica is soluble in water at high temperatures forming *monosilicic acid*, $(\text{Si}(\text{OH})_4)$ ^[20] and this property is used in the manufacture of quartz crystals used in electronics.^[19]



Under the right conditions monosilicic acid readily polymerizes to form more complex silicic acids, ranging from the simplest condensate, disilicic acid ($\text{H}_6\text{Si}_2\text{O}_7$) to linear, ribbon, layer and lattice structures which form the basis of the many different silicate minerals.^[20] Silicates are also important constituents of concretes.^[19] With oxides of other elements the high temperature reaction of silicon dioxide can give a wide range of glasses with various properties.^[20] Examples include soda lime glass, borosilicate glass and lead crystal glass. Silicon sulfide, SiS_2 is a polymeric solid (unlike its carbon analogue the liquid CS_2).^[19] Silicon forms a nitride, Si_3N_4 which is a ceramic.^[19] Silatranes, a group of tricyclic compounds containing five-coordinate silicon, may have physiological properties.^[23] Many transition metal complexes containing a metal-silicon bond are now known, which include complexes containing $\text{SiH}_n\text{X}_{3-n}$ ligands, SiX_3 ligands, and $\text{Si}(\text{OR})_3$ ligands.^[23] Silicones are large group of polymeric compounds with an (Si-O-Si) backbone. An example is the silicone oil PDMS (polydimethylsiloxane).^[19] These polymers can be crosslinked to produce resins and elastomers.^[19] Many organosilicon compounds are known which contain a silicon-carbon single bond. Many of these are based on a central tetrahedral silicon atom, and some are optically active when central chirality exists. Long chain polymers containing a silicon backbone are known, such as polydimethylsilylene $(\text{SiMe}_2)_n$.^[24] Polycarbosilane, $[(\text{SiMe}_2)_2\text{CH}_2]_n$ with a backbone containing a repeating -Si-Si-C unit, is a precursor in the production of silicon carbide fibers.^[24]

Applications

As the second most abundant element in the earth's crust, silicon is vital to the construction industry as a principal constituent of natural stone, glass, concrete and cement. Silicon's greatest impact on the modern world's economy and lifestyle has resulted from silicon wafers used as substrates in the manufacture of discrete electronic devices such as transistors, and in the development of integrated circuits such as computer chips.

Alloys

The largest application of metallurgical grade silicon, representing about 55% of the world consumption, is in the manufacture of aluminium-silicon alloys to produce cast parts, mainly for the automotive industry. Silicon is an important constituent of electrical steel, modifying its resistivity and ferromagnetic properties. Silicon is added to molten cast iron as ferrosilicon or silicocalcium alloys to improve its performance in casting thin sections, and to prevent the formation of cementite at the surface.

Electronics

Pure silicon is used to produce ultra-pure silicon wafers used in the semiconductor industry, in electronics and in photovoltaic applications. Ultra-pure silicon can be doped with other elements to adjust its electrical response by controlling the number and charge (positive or negative) of current carriers. Such control is necessary for transistors, solar cells, semiconductor detectors and other semiconductor devices which are used in electronics and other high-tech applications. In silicon photonics, it can be used as a continuous wave Raman laser medium to produce coherent light, though it is ineffective as a light source. Hydrogenated amorphous silicon is used in the production of low-cost, large-area electronics in applications such as LCDs, and of large-area, low-cost thin-film solar cells.

Silicones

The second largest application of silicon (about 40% of world consumption) is as a raw material in the production of silicones, compounds containing silicon-oxygen and silicon-carbon bonds that have the capability to act as bonding intermediates between glass and organic compounds, and to form polymers with useful properties such as impermeability to water, flexibility and resistance to chemical attack. Silicones are used in waterproofing treatments, molding compounds and mold-release agents, mechanical seals, high temperature greases and waxes, caulking compounds and even in applications as diverse as breast implants, contact lenses, explosives and pyrotechnics.^[25]

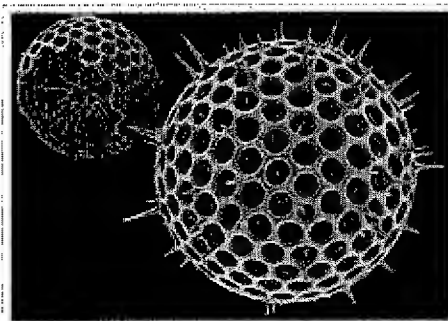
- Construction: Silicon dioxide or silica in the form of sand and clay is an important ingredient of concrete and brick and is also used to produce Portland cement.
- Pottery/Enamel is a refractory material used in high-temperature material production and its silicates are used in making enamels and pottery.
- Glass: Silica from sand is a principal component of glass. Glass can be made into a great variety of shapes and with many different physical properties. Silica is used as a base material to make window glass, containers, insulators, and many other useful objects.
- Abrasives: Silicon carbide is one of the most important abrasives.
- Silly Putty was originally made by adding boric acid to silicone oil.^[26]

Energy storage

It has been proposed^[27] that, given sufficient solar energy, silicon might be refined for use as a coal replacement

Biological role

Although silicon is readily available in the form of silicates, biology only uses it in very limited occasions in the form of silicic acid and soluble silicates. Diatoms, radiolaria and siliceous sponges use biogenic silica as a structural material to construct skeletons. In higher plants the silica phytolith (opal phytolith) are rigid microscopic bodies occurring in the cell.^{[28][29][30]} Although silicon was proposed to be a ultra trace nutrition its exact function in the biology of animals is still under discussion. It seems more clear that some plants, for example rice, need silicon for their growth ^{[6][29][30]}



Silica skeleton of radiolaria in false color.

In popular culture

Because silicon is an important element in semiconductors and high-technology devices, Silicon Valley in California is named after this element since it is the base for a number of technology related industries. Other geographic locations with connections to the industry have since characterized themselves as Siliconia as well, for example Silicon Forest in Oregon, Silicon Hills in Austin, Silicon Saxony in Germany, Silicon Valley in India, and Silicon Border in Mexicali.

See also

- Black silicon
- Covalent superconductors
- Monocrystalline silicon
- Polycrystalline silicon

- List of silicon producers
- Printed silicon electronics
- *Silicon (journal)*

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External links

- Mineral.Galleries.com – Silicon (<http://mineral.galleries.com/minerals/elements/silicon/silicon.htm>)
- WebElements.com – Silicon (<http://www.webelements.com/webelements/elements/text/Si/key.html>)

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